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13. ABSTRACT (Maximum 200 words)

This is the final report of the Boston University, Harvard University and University of Maryland MURI on Design and Control of Smart Structures. The report contains a summary of results obtained from the inception of the program in May 1997 until its conclusion in August, 2003. Over this period the researchers involved produced new and useful results in the areas of micromechanical devices (fabricated and used at ARL), micro fluidics, work on the control of boundary layer flows, work on modeling micromagnetics, and a range of patented devices including a 1024 segment controllable MEMS mirror and a novel 1000 Hz optical switch based on the control of a fluid interface. More than 60 students at undergraduate, graduate and postdoctoral levels were supported under this project and over 160 papers have appeared acknowledging support from the grant.

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Statement of Problem Studied

For the purposes of this MURI ''Smart Structures'' may be thought of as solutions to technological problems that use the controllability of physical effects such as magnetostriction, electrostriction, piezoelectric effects, and electro-osmosis to achieve their function. This represents an emerging area of engineering made possible by new developments in material science, micro fabrication and the availability of analog and digital electronic modules capable of generating the precise high frequency waveforms necessary to take advantage of such effects. The problems studied include fundamental questions on the modeling of magnetic materials operating in unusual modes, the development of new fabrication techniques for MEMS devices that can take advantage of smart materials and smart controls, modeling magnetic hysteresis in materials such as terfonal, new techniques in the control of fluids, development of larger and more capable arrays of MEMS mirrors, and new developments in NMR pulse design.

Summary of the Most Important Results

The goal of the research done under the support of this MURI is to advance the state of the art in the active control of materials and structures. We organize the summary of our results around topics according to the sub headings appearing below.

Micro fluidics: Progress on the development of theory and experiment in the area of small fluidic systems has included control of boundary layer flow, work on the control of position of fluid interfaces and peristalticly driven channel flows. Applications of the former in the area of optical switching have been developed whereas applications of latter have been made in micro mixing. We have built and analyzed an optical switch capable of switching a light beam at up to 1000 Hz by using the electrostatic deflection of a conductive/dielectric fluid interface approximately .025 inches in diameter and .01 inches deep. Optimal control principles played an important role in improving the switching speed. Because an important part of many systems being developed for micro analysis and processing is mixing in low Reynolds number flows we developed new analysis methods for understanding such mixing processes. This has been reported in the literature and is being further explored in collaboration with other groups at Harvard. New scaling laws have been developed for investigating laminar flow patterning in small scale structures. We have given a proof of concept of liquid-liquid interface spatial light modulator, We have given an analysis of dispersion in nonuniform flows in a parameter region appropriate to the investigation of mixing at small scale. This is important for chemical analysis techniques, combustion and a number of other micro fluidic applications. Electro-osmotically driven flow due to surface inhomogeneities (w/ Ajdari, Long) high-frequency peristaltic flow in a closed cavity - applications to mixing (w/ Selverov) micro-pump/motor (w/ Day) dispersion in radial flow and spatially varying configurations (w/ Brenner and Selverov)) syringe-driven flow (w/ Katopodes, Davis)

In addition there have been experiments on the development of vortex models in support of work on active flow control as well as wide ranging experiments on controlling boundary fluid flows using arrays of microjet actuators including the first detailed parametric study of optimal jet patterning for optimal control of stall due to high

angles of attack in airfoils. The vortex models capture the many results from flow-control experiments. The experimental component is detailed in the Boston University thesis of S.H. Lee and the vortex modeling appears in several papers by A.C. Smith and J. Baillieul. Considerable effort was made during the period of performance of the grant to interact with and transition results to researchers in other groups interested in these problems. In addition to technical presentations at conferences, Wright-Patterson AFB, and the United Technologies Research Center, and Boston University, in partnership with the United Technologies research Center sponsored an international workshop on The Control of Flow Separation, at the center in October of 1999.

Modeling micromagnetics: We have developed new low-order mathematical models of hysteresis nonlinearity. These can be used in the selection of materials for the control surfaces of aircraft, rotorcraft and submersibles. The refined dissipation models applicable to magnetostrictive elements are of importance for numerical simulation. These are expected to lead to new software tools for the design of actuators. The models we have developed for magnetoelastic systems, based on the Landau-Lifshitz-Gilbert equations can be used to obtain predictions of hysteresis curves. These are key to predicting the efficiency of devices. Cayley transform methods have been developed to produce accurate algorithms for micromagnetics, with projected applications in magnetostrictive actuator modeling. These methods have been tested in small size grids. This work was presented at workshops in magnetics (George Washington University, May 2001 and Princeton University, June 2001).

Work on modeling and control of hysteresis using Preisach models has led to the successful demonstrations of inversion of hysteresis in magnetostrictive actuator control. New methods based on finite automaton models of hysteresis has been developed together with a robust control theory for systems with hysteresis. (See thesis of Xiaobo Tan, jointly supervised by J. S. Baras and P. S. Krishnaprasad), In the joint work of X. Tan, J. S. Baras and P. S. Krishnaprasad, new infinite dimensional models of dynamic hysteresis have been investigated and control algorithms have been developed for tracking smart actuators with hysteretic behavior. These algorithms have been successfully tested and validated in the laboratory.

Adaptive Optics: High-resolution laser-wavefront modulation addresses a critical military need in a system that also offers near-term promise in the commercial sector. Prototype micromirror arrays with 25 or 100 pixels that have been fabricated at BU's Photonics Center have been incorporated into test beds for laser communication and/or adaptive wavefront control at Army Research laboratories (2), Lawrence Livermore National Laboratories (3), Lockheed Martin Missile Systems, NASA's Jet Propulsion Laboratory, The University of Victoria, Imperial College, the Rochester Visual Sciences Center, the Schepens Eye Research Institute, and Adaptive Optics Associates Corporation. The MURI/ARL collaboration benefits from strong and long-standing synergy between the ARL's Intelligent Optics Laboratory and Boston University's Precision Optics Laboratory. This work together has produced eight collaborative papers in archival journals and conference proceedings, and has resulted in four specially-organized technical conference sessions at annual meetings of the Society of Photo-optical Instrumentation Engineers (SPIE) on the topic of high resolution wavefront control. This collaboration, supported by the ARL Cooperative Research Program, has resulted in the following milestones:

1. The fastest adaptive optics control loop ever demonstrated (11kHz)
2. The first real-time adaptive optical imaging system to improve resolution using MEMS
3. The first demonstration of a laser-communication link using real-time adaptive compensation and a MEMS mirror
4. A comprehensive analysis of the optoelectromechanical performance of MEMS DMs in adaptive control systems, which appeared in Applied Optics (2001).

We have developed new techniques for high resolution optical phase distortion suppression, correcting for the effects of atmospheric turbulence on laser beams. This work is in collaboration with Dr. Mikhail Vorontsov of ARL and testing has been done both at ARL and at Boston University. Proof-of-concept experimental demonstration of the liquid crystal light valve (LCLV)-based high resolution wave-front control system (nonlinear Zernike filter realization) Simulation results show effectiveness against atmospheric turbulence Global nonlinear stability analysis for the continuous system model of the wave-front control system Patent disclosure (PS-2001-078) jointly to University of Maryland and Army Research Laboratory: Wave-front phase sensors based on optically or electrically controlled phase spatial light modulators for wave-front sensing and control (M.A. Vorontsov, E. W. Justh, L. Beresnev, P. S. Krishnaprasad, J. Ricklin). In joint work with Eric Justh, and in collaboration with Dr. Mikhail Vorontsov and colleagues at the Army Research Laboratory, significant progress has been made in othe areas of adaptive optics as well

MEMS Fabrication: Rapid progress has been made in the design of MEMS mirrors, and MEMS arrays of silicon-based microvalves as well as in the design and fabrication of arrays of silicon-based MEMS piston actuators for applications in adaptive optics using deformable mirrors. The project capitalizes on a proven and highly successful collaboration between researchers at the Boston University Photonics Center and researchers at the Army Research Laboratory. One project involves an optical system consisting of a BU 324 element silicon spatial light modulator embedded into an optical free-space laser communication link to allow high speed control of the wavefront phase. This system is being used in research concerning compensation of path aberrations and enhancement of security in point-to-point data links.

Much of the micromirror technology developed through this project has been licensed by Boston University for production by Boston Micromachines Corporation (BMC). Commercial sales of this pilot product in the past two years have exceeded $400K. In a recent collaboration supported by DARPA, the Boston University/BMC team has fabricated next-generation device with 1024 mirror pixels and improved optical quality. The military impact of micromirrors produced through the MURI research is measurable in terms of superior targeting capability for laser-guided ordinance, and improved stealth in photonic point-to-point communications. The commercial impact will felt in laser communications and biomedical instrumentation for retinal imaging.

Control Architectures: Based on earlier work by Harvard colleagues, the Boston University group established the first statement of what has become known as the Data-rate theorem, placing bounds on the minimum data rate required to stabilize a system.. The design of methods for optimizing communication patterns appropriate for controlling arrays, and the data-rate theorem mentioned were announced in a paper and presentation given at an ARO workshop on smart structures at the Pennsylvania State University, in August 1999. This work has led to ongoing developments in communications and control which is being pursued with support of the

Communicating
Networked Control. The BU/ARL collaboration, supported by the ARL Cooperative Research Program, has resulted in the following milestones: The fastest adaptive optics control loop ever demonstrated (11kHz), The first real-time adaptive optical imaging system to improve resolution using a MEMS link with real-time adaptive compensation and a MEMS mirror and a comprehensive analysis of the optoelectromechanical performance of MEMS digital mirror in adaptive control systems. (Applied Optics (2001)

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